A Radiative Transfer Model for Acoustic Propagation in Ocean Sediment Layers

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LONG-TERM GOALS

The propagation of mid-frequency (1-10 kHz) acoustic waves in shallow water regions (depths of 100-200 m) is strongly influenced by the characteristics of the ocean bottom. While there has been much progress in developing and validating bottom scattering models, much of the focus has been in the high frequency regime with comparatively less focus in the mid-frequency. This is an important topic, since in the mid-frequency regime the acoustic field can penetrate the rough interface into the sediment and undergo multiple scattering from sediment stratification and volume inhomogeneities. In this work, the long-term goal is to develop an understanding of the spatial and temporal characteristics of the acoustic field through a rigorous modeling and measurement effort. In addition, the feasibility of using tools such as chirp sonar for bottom characterization will be considered and assessed.

OBJECTIVES

The objective of this research is to examine the acoustic scattering physics in the mid-frequency regime to isolate and characterize the scattering contributions due to bottom roughness, sediment stratification, and embedded volume scatterers. A further objective is to evaluate the use of a chirp sonar system for characterization of the ocean bottom. This will provide a means for accurately quantifying parameters such as reflection losses and bottom penetration over a broad frequency range in support of Navy sonar applications.

APPROACH

The technical approach for this work is as follows:

1) Identification of a mathematical model for ocean bottom scattering: The Radiative Transfer (RT) formulation was identified as a promising framework to study random media scattering, due to its ability to handle combined layer and volume scattering[1-3]. The RT formulation has been successfully applied in electromagnetics remote sensing, in geometries similar to the ocean bottom sublayers (i.e. discrete scatterers within parallel-plane layers). It has also been suggested

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14. ABSTRACT
The propagation of mid-frequency (1-10 kHz) acoustic waves in shallow water regions (depths of 100-200 m) is strongly influenced by the characteristics of the ocean bottom. While there has been much progress in developing and validating bottom scattering models, much of the focus has been in the high frequency regime with comparatively less focus in the mid-frequency. This is an important topic, since in the mid-frequency regime the acoustic field can penetrate the rough interface into the sediment and undergo multiple scattering from sediment stratification and volume inhomogeneities. In this work, the long-term goal is to develop an understanding of the spatial and temporal characteristics of the acoustic field through a rigorous modeling and measurement effort. In addition, the feasibility of using tools such as chirp sonar for bottom characterization will be considered and assessed.

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in the acoustics community[4] for seismics[5] and material analysis[6], but had not yet been applied to ocean acoustics.

2) Comparison of the RT model with a classic scattering model: since the RT equation can be derived from fundamental principles of wave propagation, its results can be compared to classic models. The RT model for ocean bottom scattering will be compared to the integral equation method using either weak scatterers (Born approximation) or small scatterers (Rayleigh solution[7]). The RT formulation has the advantage of providing a solution for both cases.

3) Implementation of the Transient RT formulation: Most of the research on Radiative Transfer has been done for steady state conditions (i.e. the media is excited by a permanent source at a single frequency), but most of the experiments on scattering are conducted by exciting the media with broadband finite pulses[6,8]. The Transient RT formulation will allow handling this kind of excitations.

4) Tank experiments to validate the model: a measurement facility for tank experiments has been implemented at the NEAR-Lab, PSU. Scaled tank experiments will be conducted at ultrasound frequencies using well characterized random media (a substrate slab with embedded scatterers such as glass beads). These measurements will allow comparison of the experimental scattering levels to the predicted values obtained from the RT simulator.

In tandem with the development of a new ocean bottom RT, analysis of data from the Shallow Water 2006 experiment (SW06) was ongoing, providing knowledge of bottom structure and potential for model validation.

WORK COMPLETED

- The approach for Ultrasound Radiative Transfer presented by Turner and Weaver [4] has been adapted to Ocean Acoustics, for a three-layer model that consists on a water column on top, a finite layer of sediment with discrete spherical scatterers in the middle and an infinite half space at the bottom. The implemented RT model assumes flat boundaries between layers and uses elastic plane wave reflection and transmission coefficients to model the coupling of energy. The solution given by this model corresponds to steady-state excitations. The RT formulation for ocean bottom scattering and demonstration of the conservation of power in lossless media are explained in detail in Quijano et al[9-11].

- Implementation of the Transient RT equation: Results for the single scattering solution of the transient RT equation found in the literature where reproduced at the NEAR-Lab[12], and the implementation of the multiple scattering solution is in progress. The Transient RT formulation is based on several publications[6,8] , and it will be used to model volume scattering from the sediment as a result of applying a broadband finite length pulse of energy. This resembles more closely the experimental conditions of tank experiments and field experiments (like SW06) for comparison and validation of the RT model.

- Preliminary tank experiments to measure scattering due to random particles have been performed at the NEAR-Lab measurement facility. Several materials (paraffin wax, agar gel and Versagel®

by Penreco, Indianapolis, IN) have been tested to be used as a background to manufacture slabs with embedded random scatterers. From those materials, Versagel® exhibits the best properties: similar acoustic impedance as water and low absorption, which allows deep penetration of the incident pulse and interaction with embedded scatterers.

- A major future extension of the current model is the incorporation of rough interfaces via Kirchhoff scattering.

RESULTS

a) Theoretical results:

Details of the theory and implementation of the RT equation for steady state excitations is explained in a published paper[10]. In summary, the RT equation gives a solution to the general problem depicted in figure 1, where the incident longitudinal wave in the water column can excite multiple streams of longitudinal($S_1^{L1\downarrow}$) and shear (not shown) energy in the sediment containing random scatterers.

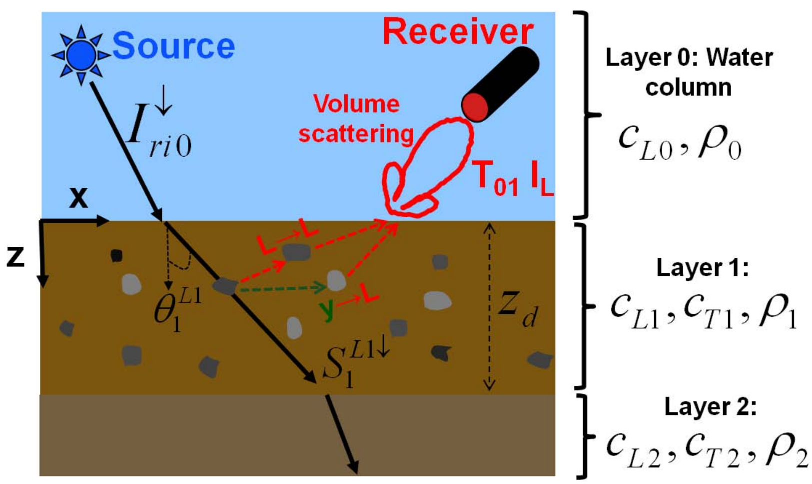


Figure N.1: The incident intensity in the water column $I_{ri0}^{\downarrow}$ interacts with the water-sediment interface, giving rise to a coherent stream of intensity $S_1^{L1\downarrow}$ transmitted into layer 1. This intensity becomes a "source" of diffuse intensity in the RT equation, and is used to compute the total amount of volume scattering $T_{01} I_L$, where T_{01} is the transmission coefficient at the sediment-water interface. Each elastic layer is characterized by the mass density ρ_n, and the longitudional and shear sound speeds, c_{Ln} and c_{Tn}. At any scatterer, transformations of energy from longitudinal (L) to shear (x or y) polarization and vice versa are included in the model.

The RT equation that describes figure 1 is[4,10]:

$$\cos\theta \frac{\partial I_L(\theta,\emptyset,z,t)}{\partial z} + \frac{1}{c_L}\frac{\partial I_L(\theta,\emptyset,z,t)}{\partial t} = -\eta\sigma_L I_L(\theta,\emptyset,z,t)$$

$$+\frac{\eta}{4\pi}\int_0^{2\pi}\int_0^{\pi}\left[P_{LL}I_L + P_{xL}I_x + P_{yL}I_y\right]\sin\theta' d\theta' d\emptyset' + S_{1L}^{\downarrow} e^{-\frac{\eta\sigma_L z}{\cos\theta_1^{L1}}}\delta\left(t - \frac{z}{\cos\theta_1^{L1} c_L}\right) \quad (1)$$

where I_L is the longitudinal diffuse specific intensity, η is the number of scatterers per volume in the random media, t is the time, σ_L (or σ_T) is the scattering cross section of a single scatterer due to an incident longitudinal(or shear) wave, P_{LL} , P_{xL} and P_{yL} are the cross polarizations from longitudinal, shear horizontal and shear vertical energy into longitudinal energy, respectively. The term $S_1^{L1\downarrow}$ represents the coherent (longitudinal) energy that propagates into the sediment, and similar terms can be added to account for multiple bounces of this coherent intensity between the boundaries of the layer. $S_1^{L1\downarrow}$ can be seen as a "source" term of the diffuse intensity in (1). The δ(.) Kronecker function is used to meet the causality condition of the source, and it indicates that the excitation is a short impulse of energy. The RT equation can be transformed to the frequency domain as[6]:

$$\cos\theta \frac{\partial I_L(\theta,\emptyset,z,\Omega)}{\partial z} = -\sigma_c I_L(\theta,\emptyset,z,\Omega)$$

$$+\frac{\eta}{4\pi}\int_0^{2\pi}\int_0^{\pi}\left[P_{LL}I_L + P_{xL}I_x + P_{yL}I_y\right]\sin\theta' d\theta' d\emptyset' + S_{1L}^{\downarrow} e^{-\frac{\sigma_c z}{\cos\theta_1^{L1}}}; \quad (2)$$

where $\sigma_c = \eta\sigma_L - \frac{j\Omega}{c_L}$ is a complex variable and Ω is the frequency domain that represents the rate of change of the intensity. Figure 2 shows the difference between Ω and the frequency of the source in the water column, ω>> Ω.

The steady state solution of I_L (i.e. making $\partial I_L(\theta,\emptyset,z,t)/\partial t = 0$ in (1)) has been discussed in a published paper [(4)]. Since the form of (2) is similar to (1) except for the complex valued σ_c, a similar approach is used for the transient RT equation in the Ω domain, followed by a Fourier synthesis.

Figure N.3 shows a comparison between results available in the literature[6] and a simulation obtained at the NEAR-Lab for the solution of the transient RT equation (single scattering). This solution is obtained by ignoring the contribution of the double integral in (2). In this example, Turner and Weaver[6] also calculate the full solution (including multiple scattering) for different values of the background attenuation, and as expected, it converges to the single scattering solution for large values of background attenuation where the multiple scattering effects are minimized.

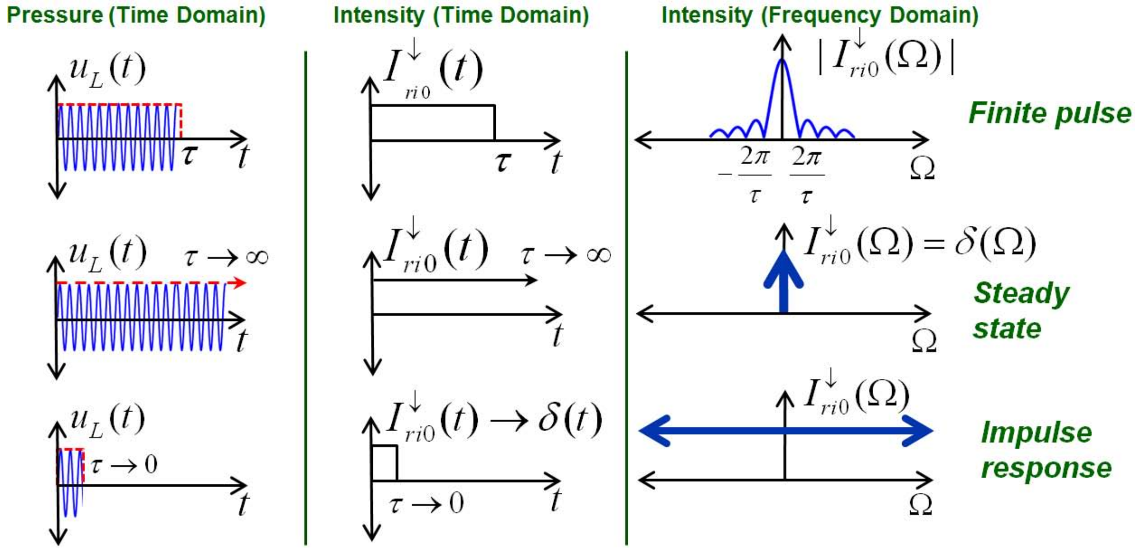


***Figure 2:** Schematic interpretation of the relationship between the excitation (signal $u_L(t)$ shown in blue, with frequency of ω rad/s), the corresponding specific intensity (rate of change of Ω rad/s) and the Ω frequency domain used to solve the Transient RT equation. The impulse response can be used to compute the solution to more complex excitation signals (i.e. chirps).*

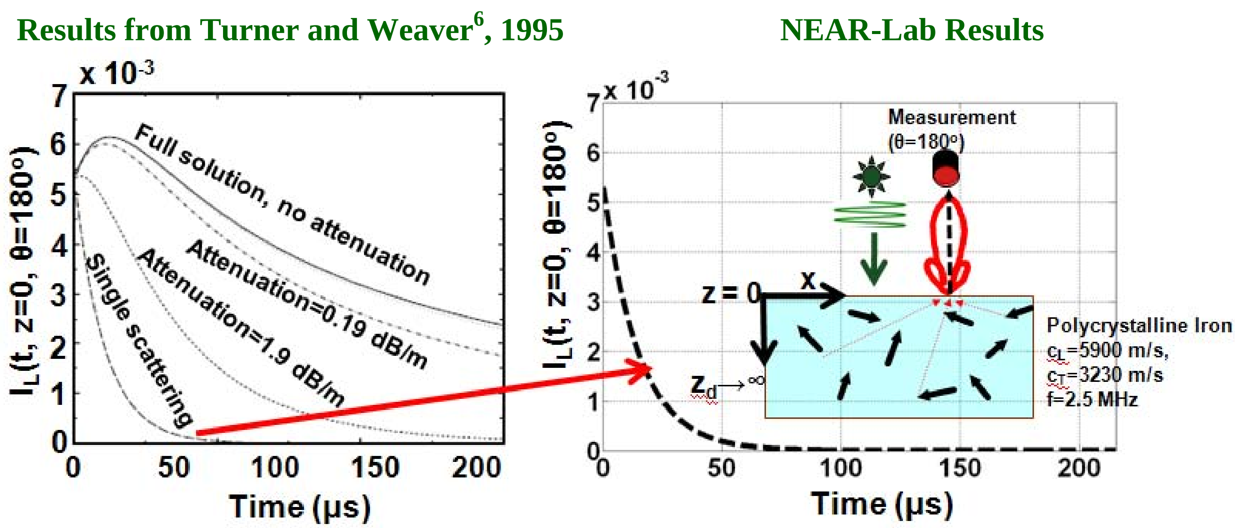


***Figure N.3:** Example of the solution of the Transient RT equation for single scattering, and comparison with published results by Turner and Waver[6]. The simulation computes the backscattered diffuse intensity I_L from polycrystalline iron media when the excitation is a short impulse with f=2.5 MHz. The full solution for different values of background attenuation was computed by Turner and Waver[6].*

The implementation of the full solution of the transient RT equation at the NEAR-Lab is a work in progress.

b) Experimental results:

Versagel® gel was used as a background material to manufacture slabs with random scatterers, and preliminary work has been done to characterize the acoustic properties of this material. At room temperature the gel has a rubber-like consistency that makes it suitable for holding random scatterers. For sample preparation, it can be melted at 100^{o} C and poured into molds of the required dimensions. The gel is composed mainly of mineral oil, which has a density of 840 kg/m^3 and compressional sound speed of 1567 m/s. To measure acoustic transmission through this material, 2 slabs of 22 cm x 22 cm and 2.5 cm thickness where manufactured, one containing random scatterers (fractional volume η=0.05) and one with no scatterers. The random particles are soda-lime glass spheres (MO-SCI Specialty Products, Missouri) of 1 mm diameter. Figure N.4 shows a diagram and pictures of the experimental setup.

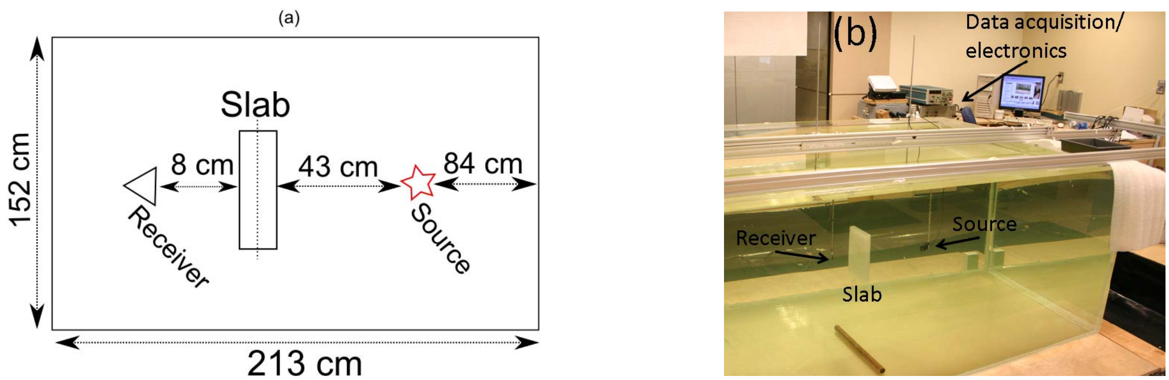
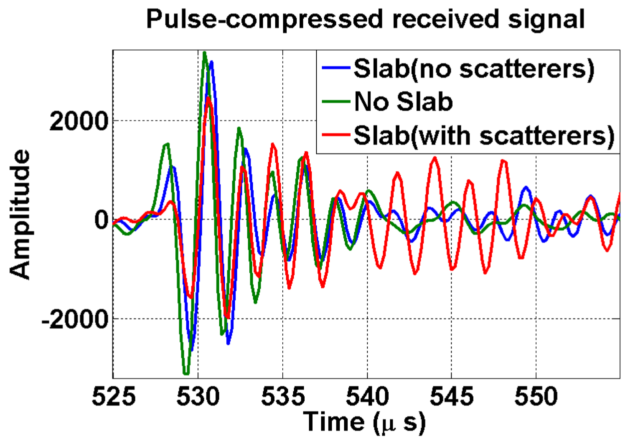


Figure N.4: (a) Top view diagram of the experimental setup to measure transmission through gel slabs; (b) Picture of the experimental setup at the NEAR-Lab, using a TC3029 transducer as a source and a TC4038 hydrophone as a receiver. The signal was transmitted/recorded at 5 MS/s using the data acquisition board NI PCI-6110.

Linear chirps of 10 ms duration and frequency band 200 kHz to 600 kHz where transmitted/recorded using a data acquisition system PCI-6110 controlled by a Labview interface, and figure 5 shows examples of the received signals after pulse compression.

First, the pulse was transmitted through the homogeneous slab (blue) and it is compared to the signal received in the absence of any slab (green). In this case, both received signals match closely, indicating no absorption in the gel and acoustic impedance similar to water. Comparison with the pulse transmitted through the non-homogeneous slab (red, glass scatterers) shows a decay in the received amplitude as well as time spreading of the original pulse, due to scattering from the glass beads. The next step of this research will be on comparison of the experimental backscattered signal to a classical model and to the RT model, using slabs with different fractional volumes up to the limit of dense media (η>0.1).

(a)



(b)

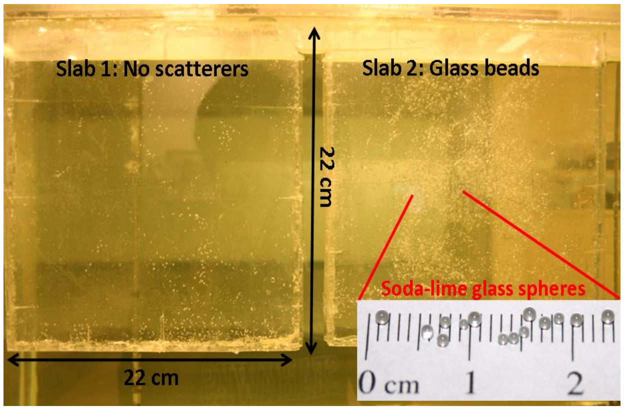


Figure N.5: (a) Time snapshot of the pulses transmitted through slabs of gel without scatterers (blue) and with scatterers (red), compared to the signal received in the absence of any slab (green). (b) Images of the manufactured gel slabs and zoom-in of the glass spheres used as scatterers.

IMPACT/APPLICATIONS

Many Navy sonar systems operate in the mid-frequency (1-10 kHz) band (for example, surface ship active ASW, SQS 53). In shallow water regions (depths of 100-200 m) the performance of these systems is strongly influenced by the presence of environmental variability. The impact of this work is to provide an understanding of the spatial and temporal characteristics of the acoustic field in the mid-frequencies in order to optimize sonar performance.

RELATED PROJECTS

Physics-Based Processing for Sonar Mapping of Coral Reefs; (FY07, sponsored by the Nature Conservancy).

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PUBLICATIONS

J.E.Quijano and L.M. Zurk, Radiative Transfer theory applied to ocean bottom modeling. J. Acoust. Soc. Am., 126(4), October 2009 [IN PRESS].